Wireless Sensor Network Solution for Sustainable Food Production

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***Abstract*—Environmental monitoring has become a key aspect in food production over the last few years. Due to their low cost, low power consumption and flexibility, Wireless Sensor Networks (WSNs) have turned up as a very convenient tool to be used in these environments where no intrusion is a must. In this work, a WSN application in a food factory is presented. The paper gives an overview of the system set up, covering from the initial study of the parameters and sensors, to the hardware-software design and development needed for the final tests in the factory facilities.**

***Index Terms* — Environmental monitoring, Sensors, Sustainable food production, Wireless Sensor Networks.**

I. INTRODUCTION

FOOD industry is one of the main industrial activities in southern Europe, Germany and the United Kingdom. France, Italy, Spain and the previous two, cover now up to 60% of the food business in Europe [1].

Water and air quality monitoring are essential for the correct understanding of the production processes in this kind of factories. By means of knowing the composition of the waste water and air emissions, it is possible to foresee a malfunction in the production chain which can be translated into water and power savings and into a sharp reduction of liquid and solid wastes. Apart from these reasons, environmental monitoring is now a must due to European and local regulations.

Non intrusion and simplicity are essential in environments where food is involved and where the production processes cannot be interfered for health reasons. WSNs are then presented as a suitable solution for these applications due to their non-intrusion features and dynamic capabilities. Unlike other traditional methods used in most of the food factories, WSNs offer non expensive and continuous measurements without human intervention.

It is possible to find numerous international laws about environmental care related to food industry. It is not the aim of this paper to give a deep survey about them, but it is worth to name some of the most important ones and give an idea of the parameters they required. For instance, the well-known ISO 14000 for the environmental management and Life cycle assessment [2], the Directive 2008/1/EC on Integrated Pollution Prevention and Control, that organizes all industries working with raw animal material used in any food production by their production volume [3], or the Referent Document on Best Available Techniques (BAT) in the Food, Drink and Milk Industries, which details all the activities referred in the annex 1 of the European Council Directive 2008/1/EC, are some of these examples. According to the analysis of the best available techniques in the last document, some parameters and threshold values are defined for the waste water. Among these parameters it is possible to find the Biochemical Oxygen Demand BOD_5 or the Chemical Oxygen Demand COD apart from some ion concentrations.

It is at this point where the scope of the application must be defined. WSNs can provide low-cost, low-power, unattended and non-intrusive solutions. WSNs can offer a more suitable solution compared to wired systems due to their easier set up in certain environments such as factories where the production chain cannot be interfered. Therefore, they are ideal for non-reachable places and most important, allows a higher mobility so the devices can be displaced to compare emission levels in different areas directly by the user. However, WSNs have some limitations related to the measurement of some of these environmental parameters. For instance, when talking about oxygen demands, the measurement processes require temperature and light conditions that are difficult to maintain with an unattended system. The same happens with phosphorus and other ions. Thus, it will be necessary to make indirect measurements or, at least, to monitor alternative parameters capable of generating alarms in case of a problem.

It is possible to find many WSN applications related to environmental monitoring in the literature. Watershed and river monitoring shown in [4], [5], energy management solutions to reduce the amount of resources needed and atmospheric emissions in factories [6] are some of these examples. There is also a relevant work made by the CSIRO Center in Australia [7]. Their work includes a complete set of environmental and agricultural applications together with a review of past and future opportunities in WSN applications.

When talking about water monitoring, it is possible to find a lot of references in China where pollution has become one of the biggest problems for the current government. For instance, in [8], a monitoring system is proposed to measure water parameters such as dissolved oxygen, pH, conductivity and temperature for river and lakes monitoring. In this work, the convenience of using WSNs in terms of price, flexibility and real time processing are explained.

Even though WSN platforms are mostly developed by electronic engineers, environmental applications usually require the participation of environmental engineers. In [9] a WSN deployment is shown from the environmental point of view and not only from the hardware-software side.

The paper is organized as follows. Section II gives an overview of the environment where the deployment takes place together with all the information about parameters and sensors. Section III describes the WSN platform from both hardware and software points of view. Section IV details the software platform for data collection. Section V shows the results after tests in the factory facilities and Section VI finishes with some conclusions about the work.

II. ENVIRONMENT AND PARAMETERS

A. The Factory

The deployment tests of the sensor network will take place in a meat production factory called *Assofood* located in the Province of Modena (Italy). A short description of the structure of the factory is going to be presented to evaluate the proper location of the sensors. Some issues such as wireless communications and sensor placing, facing several problems caused by the presence of machines and metallic objects, are also evaluated.

The factory consists of four different areas as seen in Figure 1:

1) *Red area*: special conditions of hygiene, security. Temperature, humidity and pressure controlled due to direct exposure of the meat.
2) *Green area*: area dedicated to packaged product processing. Labeling, storage and shipment processes take place in this area.
3) *Orange area*: semi-processed and mixed meat products.
4) *Blue area*: this area contains all the necessary machines and resources to ensure the correct operation of the factory (refrigeration unit, electric center, thermic center, control of the water circuit). Alkaline vapors given off by the washing rooms take particular importance for this WSN application.

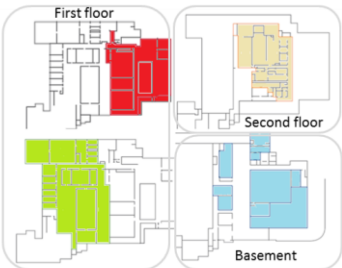

Figure 1: Factory areas

B. Parameters & Sensors

An overview of the parameters and sensors used are explained in this section.

1) *Conductivity*: this is the ability to conduct electricity as a result from the motion of electrically charged particles in the water. Since electrical current is transported by ions, the conductivity measurement increases as the concentration of ions rises. Thus, the higher the ion concentration is, the higher the conductivity becomes. In this way, conductivity provides an indirect measurement of the ion concentration present in the water. The need to measure conductivity appears as a result of the difficulties encountered in measuring ion concentrations such as phosphorus, sulfates or chlorides, which are the most common ions required by every regulation.

   Sulfates and chlorides are normally monitored using Ion Selective Electrodes (ISE). This method presents several advantages such as relatively low cost, quick response and use in turbid and colored solutions in which other methods such as photometry cannot be applied. However, this method is not suitable for online monitoring. For instance, changes in temperature affect the balance of the solution, calibration is required very often, reagents must be added to the water sample and other ions can produce interferences in the concentration value.

   In the case of the phosphate or phosphorous concentrations, there are two official measurement methods: the Molybdenum blue method and the Vanadate/molybdate yellow method [10]. Both methods are based on measuring the concentration of ortho-phosphate by taking a photometrical measurement after the sample is treated with ammonium molybdate and ammonium vanadate, respectively.

   As it can be observed, the peculiarities of these methods make these measurements difficult to achieve for an online monitoring system. That is the reason why the conductivity monitoring is used as a way to detect the increase of ion concentration in a water sample.

   The sensor chosen to carry out this measurement is a conductivity probe designed by the “Centro Nacional de Microelectrónica” (CNM-CSIC). This sensor can be easily adapted to the WSN platform to be used while at the same time it has a very convenient price.

   The sensor is a 4-electrode conductivity probe (two current and two voltage electrodes). By contrast with the 2-electrode probes, this has a wider measuring range with a single cell constant while polarization can only occur on the current electrodes [11].

   Conductivity is measured as the opposite of resistivity between two electrodes, where both the area and the distance between them affect the measurement. The relation between area and distance is called cell parameter. In this way, conductivity can be expressed as: $C=k/R$. Where R is the resistance and k is the cell parameter. When an increase of the ion concentration happens, the resistance measured between the current electrodes decreases creating a change on the voltage electrodes. Monitoring this voltage variation allows to determine the change in the conductivity value.
2) *pH*: This is a measure of the activity of the hydrogen ion. A pH range of 6 to 9 pH units is necessary to protect the ecosystem and assure the stability of several organisms. Also, controlling the pH level can avoid toxic effects from certain components. For example, iron concentrations above 4 mg/l do not produce toxic effects with a pH value of 4.8. However, the same amount of iron with a higher pH value results in a substantial toxic effect. Even though the pH measurement is no different from any other ion, a better solution has been found based on an ISFET. This sensor works as a MOSFET that changes its gate voltage depending on the concentration of hydrogen ions. In this case, calibration is not as frequent as in the ISE probes and the cost is lower than other commercial solutions. Both the conductivity and pH sensors are enclosed in a custom design case as shown in Figure 2.

Figure 2: pH and Conductivity probes

3) *Carbon Dioxide*: most of the carbon dioxide gas emitted in food processing plants is the result of the use of

electricity, natural gas, coal or other energy sources, as well as emissions from waste water treatment plants, refrigeration systems, composting operations, etc.

The option selected for this application is a solid-state potentiometric gas sensor [12]. This is a passive sensor with a range of 500 ppm to 90%, small size and low cost. Solid-state sensors absorb gas into the sensor surface, changing the resistance of the sensor material. When the gas disappears, the sensor returns to its original condition. No sensor material is consumed in the process, and hence the solid-state sensor offers a long life expectancy. It is a two electrode sensor that creates a voltage output in a way that approximately linear with respect to the logarithm of the gas concentration, as defined by Nernst's equation, Figure 3:

$$Eeq = Eo + 2.303\frac{RT}{2F}\log p[CO2] \quad (1)$$

Where Eeq is the measured voltage (mV), E_O is the offset voltage and 2.303RT/2F is the Nernstian slope (mV/decade concentration).

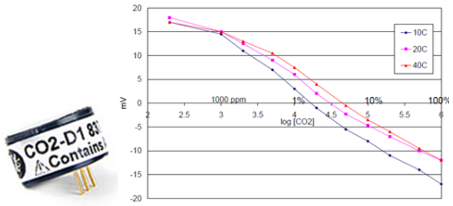

Figure 3: Carbon dioxide sensor response

4) *Water temperature:* Temperature is an important water quality parameter that is relatively easy to measure and has a direct impact on the organisms living in the water.
Many aquatic organisms are sensitive to changes in water temperature, especially because it will affect other parameters, such as dissolved oxygen and salinity.
Additionally, the rate of chemical reactions generally increases at higher temperature. For instance, conductivity and pH in a solution increase as the temperature rises due to higher ion mobility. This change creates an error in the measurement that can be avoided by using a reference temperature to compensate the values as shown as follows:

$$k = ko[1 + \alpha o(Tt - To)] \quad (2)$$

Where k is the conductivity or the pH at T_t, k_o is the conductivity or the pH at To and α_o is the temperature coefficient at To. The sensor chosen is the well-known resistance temperature detector (RTD – Pt100).

5) *Air alkalinity:* alkalinity is the capability of neutralizing acids. In this case, it will be caused by the presence of Na_2O in the air that reacts with the water steam to create sodium hydroxide. The sensor used in this application consists of a piece of glass covered in a special coating. This coating is made of an organic compound (3, 3-dichlorophenolsulfonephthalein) that changes its color depending on the air pH. This sensor was designed and manufactured by the Institute of History of CSIC. In order to measure the changes in the color of the glass, it is necessary to include a colorimeter in the node. The colorimeter consists of two optical channels, red and blue, as seen in Figure 4. Each one of these channels includes a LED and a photodiode. In this way, the red path crosses the glass sensor, painted in purple, while the blue one works as a reference channel.

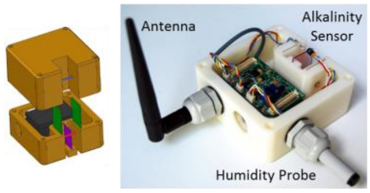

Figure 4: Alkalinity Node

The absorbance can be given by the following expression:

$$Absorbance = \log(reference / sensor) \quad (3)$$

The curve that expresses the relation between absorbance and pH can be seen in Figure 5. As it can be observed, the behavior is linear in the range of interest, 6 to 9 pH units.

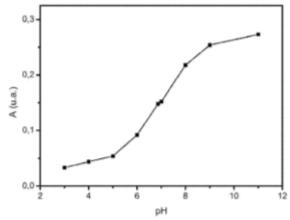

Figure 5: Absorbance vs. pH

With this pH value, it is possible to calculate the amount of hydroxyl ion and then the amount of Na_2O present in the ambient, although the results shown in this work will be given in absorbance and pH.

6) *Humidity Sensor:* the sensor used to measure the humidity in the surroundings of the alkalinity node is the commercial HM1500LF that can be seen in Figure 4. The case is made of a solid polymer structure and is calibrated within $^+/_-$ 2% at 55%HR. It has a typical 1 to 3.6 Volt DC output for 0 to100%. Humidity is necessary around the alkalinity sensor in order to know if the crystal is misty.

7) *Temperature and humidity sensor:* Apart from the humidity sensor used in the alkalinity node, it is necessary to measure the relative humidity and air temperature in some other points of the factory. The sensor used in this case is a digital sensor from Sensirion SHT11. This sensor is very convenient for WSNs due to its low power consumption, wide ranges (0-100% of relative humidity and -40 to 125 ºC of air temperature) and small size 7.5 x 5 mm.

Table 1: Parameters to be measured

Symbol	Name	Range
C	Conductivity	900µS/cm to 2 mS/cm
pH	pH	5.5 to 9.5 pH units
CO_2	Carbon Dioxide	1%
WT	Water Temperature	10ºC to 90 ºC
Alk	Air Alkalinity	[Na_2O] 0.7 to 5mg/m^{3}N
H	Air humidity	40 % to 65 %
AT	Air Temperature	20ºC to 50ºC

III. WSN PLATFORM

A. Hardware Description

WSN nodes normally require four capabilities: data processing, wireless communication, sensing and/or acting, and power supply. In order to have a flexible design, the Cookie platform [13] is divided into four different PCBs, each of them covering one of these previous functions. Every layer is connected to the following through vertical connectors as seen in Figure 6. Due to this modular design, it is possible to exchange every layer separately if different sensors, communication modules, power supply sources, etc. are needed. This modularity is very useful when adapting the node to different requirements. The four layers mentioned are listed below.

Figure 6: Cookie Node

1) *Sensor layer*: it includes conditioning circuits for both digital and analog sensors and/or actuators. They will be explained within the next section.
2) *Power supply layer*: The node can be powered from a USB cable, lithium or AA batteries or directly from the mains (using the USB connection). This layer includes a DC-to-DC converter (TPS650243) to provide the needed current and voltage level with high efficiency. This power management IC provides three step-down converters (up to 97% efficiency) that enter in low power mode with light load for maximum efficiency across the widest possible range of load currents, and two LDOs for lower currents. It can also recharge a 500mAh battery in only one hour from any USB connection.
3) *Communication layer*: this layer includes a ZigBee module to communicate data between nodes. The module used along this work is the Telegesis ETRX2 ZigBee module.
4) *Processing layer*: this layer includes a low power microcontroller C8051F930 from Silicon Labs and an optional Actel Igloo AGL030 FPGA. Since most of the sensors used in this application are analog and the main processor is the microcontroller, the FPGA will only be used in one of the cases to work with the temperature and humidity sensor. For the rest of the nodes, the FPGA is not required so that it can be left unsoldered to reduce power consumption and cost.

Every sensor in the application requires a different conditioning circuit so different sensor layers have been designed.

1) *Alkalinity and humidity Node*: this conditioning circuit is divided into three different parts: LED control, photodiodes control and humidity probe control. As it can be seen in Figure 6, the intensity of the LEDs is controlled by a current reference given by the microcontroller (IREF0). The LEDs can also be switched on and off completely to reduce power consumption by controlling two MOSFETs (LED_CTRL). Both the photodiodes and the humidity probe have a circuitry to adapt voltage levels to the range of the ADC. The ADC used is an external one since 12-bit accuracy is required. The communication between the microcontroller and the ADC is done via SPI. The SDN signal is in charge of switching on and off the whole sensor layer, so power consumption is reduced.

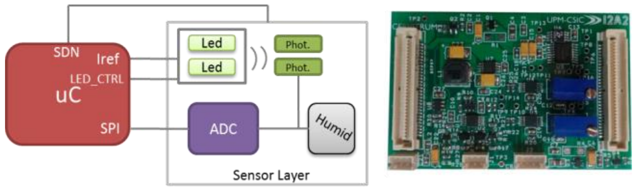

Figure 6: Alkalinity node

2) *Air temperature and humidity Node*: since the output provided by the sensor used for this measurement is digital, it does not need any additional circuitry different from the FPGA. The communication is done via pseudo-I2C with 12-bit accuracy for humidity and temperature.
3) *Carbon Dioxide Node*: due to the low impedance of this sensor, its operating life will improve with a high impedance amplifier since any current could cause instability of the different chemical substances. The circuit also includes a high-precision, low-noise voltage regulator to adjust the positive voltage in the reference electrode and a precision amplifier to adapt the output voltage, Figure 7.

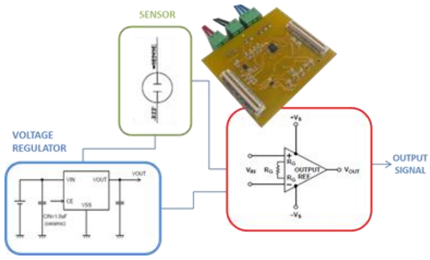

Figure 7: Carbon dioxide circuit

4) *Conductivity and water temperature Node:* the conditioning circuit for this sensor is divided into two different blocks: stimulation and measuring, Figure 8. In the stimulation part, using the programmable current reference included in the microcontroller, a sinusoidal signal current is created. This current is amplified and filtered to eliminate the DC component before it feeds the sensor electrode. In the second part, the voltage measured between the voltage electrodes is filtered to remove low frequency noise and then it is rectified to eliminate the AC component. Finally, the signal is amplified to adapt the output voltage to the range of the ADC. Due to the dependency of the conductivity with water temperature, the conditioning circuit also includes a 4-wire Pt100 sensor to compensate the error produced by the changes of temperature.

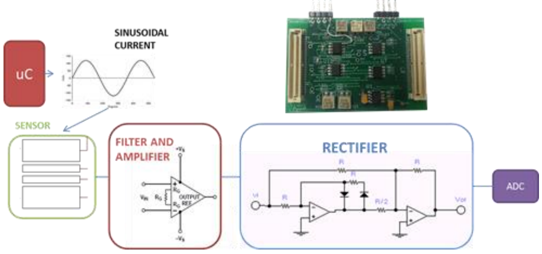

Figure 8: Conductivity Circuit

5) *pH and water temperature Node*: a schema of the conditioning circuit for the pH and water temperature is shown in Figure 9. The circuit must ensure that both the current I_{ds} (drain-source) and the voltage V_{ds} at the ISFET sensor are constant. In this way, depending on the pH value, the voltage in the gate will change. Since pH also depends on temperature, it is necessary to use a Pt100

sensor to correct the measurements. The temperature sensor is fed with current and the drop voltage is adapted to the range of the ADC.

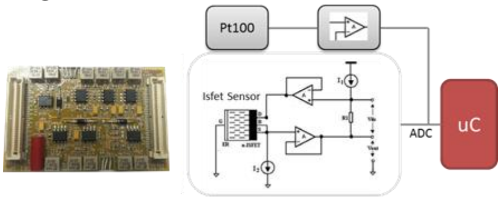

Figure 9: pH circuit

Since the measurements taken in the factory are not required very often, it is enough for the WSN to wake up and send their measurements once every hour. In order to do that, sensor nodes will have to be awake only a few minutes per hour. The rest of the time, end devices will remain asleep. Table 2 shows the approximate values for the power consumption of each type of node working on different modes of operation. During sleep modes, all the sensor modules are switched off so power is only consumed due to communication and processing layers that remain inactive.

Table 2: Power Consumption

Device Type	Operation mode: Awake	Operation mode: Asleep
End Device:		
Conductivity	50 mA	1.3 µA
CO2	30 mA	1.3 µA
Alkalinity	120 mA	1.3 µA
Coordinator/Router	9 mA	--

B. *Software Description*

Unlike other WSN platforms, the Cookies platform does not use an operating system to develop its applications but a custom API that includes functions specially designed for this platform and its applications. See the work presented in [14] for more information about the Cookies WSN API.

IV. SOFTWARE PLATFORM FOR DATA COLLECTION

In order to have a visual environment to organize the sensor network and collect data in the sink node, a MS-Windows application programmed in c# has been developed. The main features of this environment are listed below:

1) Create and configure the wireless ZigBee network.
2) Show messages and data from the rest of the nodes of the network.
3) Send messages and files to the rest of the nodes for commissioning issues.
4) Create files with the info harvested from the rest of the nodes.
5) Select the maps of the environment where the deployment is being done.
6) Select the location of the nodes to have visual information in real time about where the nodes are and what parameters they are collecting.

Figure 10 shows the look of the application.

V. TEST RESULTS

This section includes some results of the tests carried out in the Assofood factory. These tests were held on the first floor and basement. Results from the alkalinity, conductivity, temperature and humidity nodes are shown below. Neither CO_2 nor pH tests are included in this paper.

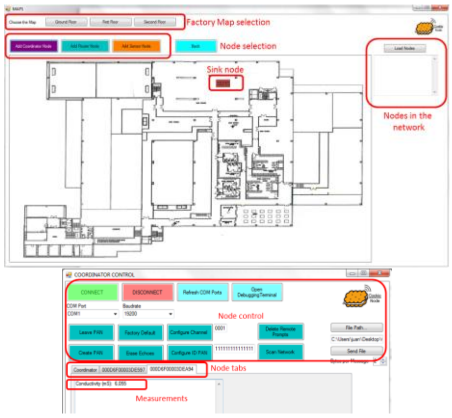

Figure 10: Data collection tool

1) *First* floor

The first tests took place on the red area in the first floor. The nodes were laid out as shown in Figure 11 creating a small local network:

- *Node number 1*: sink node, placed in an office.
- *Node number 2*: alkalinity node, placed inside a room with a washing machine.
- *Node number 3*: temperature and humidity node, placed in a corridor.
- *Node number 4*: Router Node, placed in a room with a washing machine just to check on the available coverage.

The area of interest was completely covered with a stable data flow and with no problems caused by loss of communication between nodes.

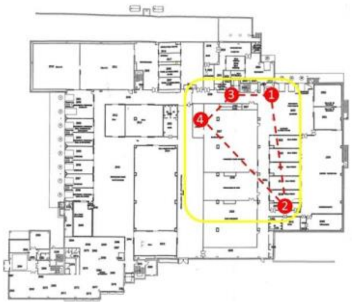

Figure 11: First floor test

Regarding the measurement of the alkalinity in the washing machine room, the node was placed inside the machine, just below the extractor fan. Because of the humidity presented, some water drops appeared in the glass so that the measurement was not feasible. To avoid this, the sensor was placed outside the machine, as shown in Figure 12. In this position, only some steam escapes the machine and reaches the node, preventing high humidity problems.

Figure 12: Alkalinity node test

After keeping the node this way, the result of two tests can be seen in Figure 13. The washing machine was not working long enough to allow the glass surface to change its color, thus this absorbance value matches a neutral pH. In this environment, both temperature and humidity are controlled so the response of this node was a constant value of 11ºC and 63%, respectively. These measures were in line with the ones provided by the factory.

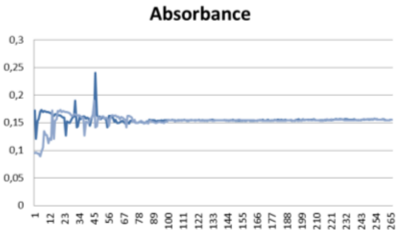

Figure 13: Alkalinity node response (absorbance vs. time)

2) *Basement*

The second experiment took place on the blue area in the basement, Figure 14. The small local network included:

- *Node number 1*: sink node.
- *Node number 2:* conductivity node, placed in the water treatment plant.
- *Node number 3*: temperature and humidity node, placed near the washing machine.
- *Node number 4*: alkalinity node, placed on the washing machine.

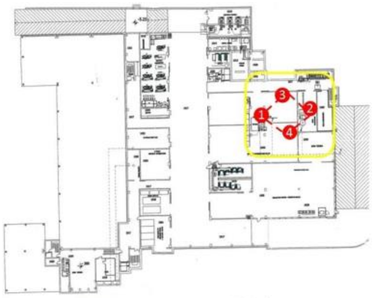

Figure 14: Basement test

In this place, the communication between the nodes was interrupted continuously. The presence of three washing machines and several metallic structures (Figure 15) and the high humidity in the area (close to 100% in the machine output) are most likely the cause of this problem. To solve this, several routers will have to be placed around in order to create a reliable connection.

Figure 15: Washing machines in the blue area.

Regarding the conductivity test, the node was placed in a waste water tank. The results from this test are shown in Figure 16. The conductivity value was 1.8 mS/cm which is higher than expected and close to the maximum permitted. This is due to the fluctuation of the conductivity value in the factory and the main reason to include this measure on the WSN application.

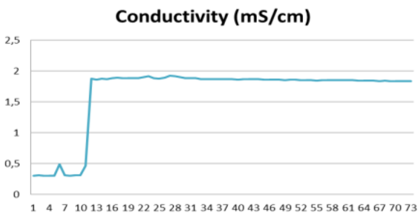

Figure 16: Conductivity test (vs. time)

Humidity and temperature values in this area were around 9ºC and 76%. Some oscillation of the humidity measure was observed due to the steam from the washing machines when these were working.

VI. Conclusions

This paper has presented an experience in the use of wireless sensor networks in an industrial environment. The main challenges of this work are related with the sensor selection and integration in the WSN platform, both the platform and the user software and the deployment itself. In this last case, the harsh environment has made the tests extremely difficult, for the radio coverage and the installation of nodes. A similar system will be tested in a cheese factory in South France during the first semester of 2013.

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